Title: Tracer Study for Characterization of Groundwater Movement and Contaminant Transport in Fractured Dolomite

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Objectives: To develop a better understanding of the movement of groundwater and contaminants in shallow, fractured, carbonate aquifers. The study was designed to 1) provide a better understanding of the hydrogeology of fractured dolomite in terms of advective flow rates and hydraulic conductivity distributions; 2) generate a data set for use in evaluating existing fracture-flow computer codes; 3) help determine the scales at which it is appropriate to approximate fractured carbonate rock as an equivalent porous medium; and 4) test the effectiveness of monitoring wells in a fractured-rock setting.

Background /Need: Fractured-carbonate aquifers provide important, but vulnerable, sources of drinking water. Effective groundwater monitoring, predictions of contaminant movement, wellhead protection, and groundwater remediation are particularly difficult in fractured-rock aquifers, and traditional groundwater monitoring techniques often fail to provide useful information in such environments. To date, most modeling of fracture flow has been unverified because few field data exist with which to calibrate available models.

Methods: Detailed site characterization, hydraulic tests, tracer tests, and preliminary modeling experiments were used to gain a better understanding of groundwater movement in fractured carbonate rocks. The authors characterized fractured dolomite at a study site located in an active dolomite quarry in Door County, WI. The quarry floor was cleared of sediment and vertical fractures were mapped and digitized. Scanline mapping of quarry walls provided information on bedding-plane fractures.

Eighteen boreholes, including five coreholes, were drilled to a depth of 35 ft. Borehole geophysical logs revealed several laterally extensive horizontal fractures and dissolution zones. Flowmeter and short-interval packer testing identified which of these features were hydraulically important. The monitoring system, consisting of multi-level samplers installed in 11 of the boreholes, was designed to monitor four horizontal fractures and two dissolution zones.

Data on the hydraulic conductivity of the fracture network were obtained from a multi-well pumping test conducted with eight 35-ft open boreholes, a second pumping test conducted after the multi-level samplers had been installed, and packer tests conducted with a 0.75-ft straddle interval. The distribution of hydraulic head was monitored in both open boreholes as well as in the discrete intervals of the multi-level samplers. Several controlled-gradient and one natural-gradient tracer tests completed at the site yielded horizontal and vertical groundwater velocities on the order of 10's to 100's of ft/day. A two-dimensional discrete fracture flow model was used to simulate one of the controlled-gradient tracer tests. Using measured data on fracture characteristics, the model reproduced data from the tracer experiment relatively well.

Results: Frequent and rapid fluctuations in hydraulic heads at the site indicate a dynamic flow system that responds rapidly to recharge events. Horizontal gradients are quite low within individual fractures because the high transmissivities allow head to dissipate; vertical gradients are higher.
Hydraulic conductivity tests at several scales show that traditional pumping tests are inadequate to characterize the study site for the purposes of groundwater movement and solute transport. The bulk hydraulic conductivity of the dolomite, measured in the open-hole pumping test, ranges from $1.8x10^{-}$

^{5} to 1.3x10^{4} ft/sec with a geometric mean value of 3.9x10^{-4} ft/sec. However, short-interval packer tests yield a much larger range of measured values (1.4x10^{-2} ft/sec to 2.3x10^{-8} ft/sec, geometric mean 9.9x10^{-6} ft/sec) as these tests were conducted over both the fracture and matrix portions of the aquifer.

Tracer tests yielded horizontal and vertical groundwater velocities on the order of 10's to 100's ft/day. These results are consistant with maximum hydraulic conductivities derived from short-interval packer tests and are inconsistent with results from traditional pumping tests.

Using measured data on fracture characteristics, the fracture network models reproduce the data from the preliminary tracer experiment relatively well.

Conclusions: Standard investigative and monitoring techniques may not be appropriate to characterize site-specific transport in fractured-carbonate aquifers. Hydraulic conductivity values determined from the open-hole pumping test under-predict tracer velocity by several orders of magnitude. The maximum hydraulic conductivity value determined from the short-interval packer tests were better able to predict measured tracer velocities. Tracer results indicate that hydraulic data alone are poor predictors of transport at small scales; transport appears to be dominated by fracture channels and small variations in fracture and matrix characteristics. Tracer distributions suggest that contaminants will be difficult to detect in these settings and that monitoring systems designed to monitor the high-permeability pathways are more likely to intercept contaminants.

Recommendations/ Implications This study has important implications for the design of groundwater monitoring systems. The hydrogeologic site characterization completed at the study site was designed to determine both "continuum" aquifer properties, determined by standard monitoring techniques (*i.e.* "open-hole" pumping tests), as well as the properties of discrete fractures. Comparison of distributions of hydraulic head and hydraulic conductivity determined by these two approaches suggests that standard hydrogeologic field techniques, including long-interval monitoring wells, are of limited use in providing information on the flow characteristics of fractured-carbonate aquifers at site-specific scales of common interest. Detailed characterizations of fracture networks and other aquifer heterogeneities are necessary for accurate monitoring, assessment, and modeling of groundwater movement in fractured carbonate rocks. Fracture-network models are more appropriate than porous-medium models for simulating flow and transport in these environments; future investigations should collect appropriate data for the use of these models.

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Final report: A final report containing more detailed information on this project is available for loan from Wisconsin's Water Library, University of Wisconsin -Madison, 1975 Willow Drive, Madison, Wisconsin 53706 (608) 262-3069.